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RESEARCH MEMORANDUM

FORCED-CONVECTION HEAT TRANSFER TO WATER AT HIGH PRESSURES AND TEMPERATURES IN THE NONBOILING REGION

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FORCED-CONVECTION HEAT TRANSFER TO WATER AT HIGH PRESSURES AND TEMPERATURES IN THE NONBOILING REGION

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SUMMARY

Forced-convection heat-transfer data have been obtained for water flowing in an electrically heated tube of circular cross section at water pressures of 200 and 2000 pounds per square inch and temperatures in the nonboiling region, for water velocities ranging between 5 and 35 feet per second.

The results indicate that conventional correlations can be used to predict heat-transfer coefficients for water at pressures up to 2000 pounds per square inch and temperatures in the nonboiling region.

INTRODUCTION

An experimental program has been undertaken at the NACA Lewis laboratory to obtain surface-to-fluid heat-transfer information over a wide range of tube wall temperatures and heat flux densities. One phase of the heat-transfer program is being conducted with water at high pressures, up to 5000 pounds per square inch, flowing through an electrically heated tube.

Initial tests have been made at a pressure of 2000 pounds per square inch in the nonboiling region, a condition which is of current interest in several experimental and theoretical investigations. Data have also been obtained at a pressure of 200 pounds per square inch to determine the reliability of the data from the apparatus. The preliminary results of these tests are reported herein.

Tests were run on an electrically heated Inconel tube with a heater length of 25 inches and an inside diameter of 0.498 inch. Heat flux for the test runs ranged between 175,000 and 650,000 Btu per hour per square foot and water velocities ranged between 5 and 35 feet per second. The data reported are for water temperatures in the nonboiling region.

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APPARATUS

A photograph of the test rig is presented in figure 1. Figure 2 is a schematic layout of the apparatus. Water leaving the electrically heated test-section tube flows through the heat exchanger where it is cooled to approximately the test-section entrance temperature. The water then passes through a circulating pump to the flow meters and back to the test section. The rate of flow is regulated by varying the speed of the pump and also by a valve in the bypass around the pump. The two flow meters for measuring low rates of flow can be bypassed at high flow rates. The system through which the water is circulated is designed for the following range of operating conditions: pressure, 0 to 5000 pounds per square inch gage; test-section inlet temperature, 70 to 800° F; test-section outlet temperature, 70 to 1000° F; flow rates, up to 30 gallons per minute.

The system is pressurized by nitrogen supplied from the storage cylinders through the regulator valve to the accumulator and test section casing. System pressures up to 2000 pounds per square inch are obtained in this manner. Higher pressures, up to 5000 pounds per square inch, are obtained by pumping water from the distilled water supply into the accumulator to force the piston upwards to compress the gas. Pressure relief valves are located in both gas and liquid lines for pressure control and safety.

The component parts of the setup are described in the subsequent paragraphs.

Electrical System

The power source for heating the test section is a 100-kilowatt transformer controlled by a saturable reactor. The transformer secondary voltage range is 1.25 to 25 volts.

Circulating System

Test section. - The test section, shown by a photograph in figure 3 and schematically in figure 4, is an Inconel tube with a heated length of 25 inches, an inside diameter of 0.498 inch, and an outside diameter of 0.689 inch. Tube wall temperatures are measured by means of 17 chromel-alumel thermocouples distributed along the length of the outside wall of the tube and a self-balancing, indicating-type potentiometer. Temperatures of the water entering and leaving the test-section tube are measured by chromel-alumel thermocouples located in tanks at both ends of the test section and by a manually operated precision potentiometer.

Both differential and direct temperature readings can be obtained from the thermocouples in the tanks.

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Heat exchanger. - The heat exchanger is a U-shaped, heavy-walled single tube with a counterflow, four-sectioned cooling jacket. It has a capacity of 350,000 Btu per hour at 152.2° F mean temperature difference.

Circulating pump. - The circulating pump is a stuffing-boxless, four-stage, variable-speed centrifugal pump designed to deliver a maximum of 30 gallons per minute against a pressure drop of 50 pounds per square inch over the temperature and pressure range of operation. Power is supplied to the pump motor from a variable-frequency motor generator set.

Flowmeter. - Three flowmeters of the rotameter type were employed, with a combined range to measure obtainable flow over the operating range of temperature and pressure. Readings are obtained remotely on manometers connected to pneumatic transmitters linked magnetically to the flowmeter floats.

Pressurizing System

Test-section casing. - The test-section casing is a stainless steel reactor-type cylinder which acts as a supercharge housing for the test section and the calorimeter tanks. It has an over-all length of 47 inches, an outside diameter of 9 inches, an inside length of 40 inches, and an inside diameter of 6 inches.

Accumulator. - The accumulator consists of a cylinder and piston. It is used to maintain an approximate balance of pressure between the circulating liquid and the supercharging gas in the test-section casing. The tank has an over-all length of 56 inches, an outside diameter of $15\frac{1}{2}$ inches, an inside length of 48 inches, and an inside diameter of 10 inches. The piston acts to separate the gas in the top of the cylinder from the liquid in the bottom.

Pressurizing pump. - The pressurizing pump is a positive displacement pump which delivers 26 gallons per hour from 0 to 5000 pounds per square inch gage.

Gas supply. - The gas supply consists of 12 nitrogen storage cylinders and a manifold rack. Each gas cylinder contains, when fully charged, approximately 244 cubic feet of nitrogen at free condition and has a pressure of from 2000 to 2200 pounds per square inch depending on the temperature.

Distilled water supply. - The distilled water supply consists of four stainless steel tanks with a total capacity of approximately 30 gallons.

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TEST PROCEDURE

The system was initially pressurized to about 100 pounds per square inch and water was circulated at a relatively high rate. Power was supplied to the test section, and the pressure was increased as the system heated. As the desired test conditions of temperature and pressure were approached, the power level and the flow were set and the system was allowed to come to equilibrium.

Runs were made at test-section inlet pressures of 200 and 2000 pounds per square inch gage. At each pressure level a range of water flow rates was covered. Several power inputs were used. At a fixed power input the maximum flow rate was limited by the temperature rise in the water passing through the test section, and the minimum flow was limited by the tube wall temperature. At high flows the temperature rise became small and the accuracy of the measurement of the rate of heat transfer decreased, and at low flows the wall temperatures approached the boiling temperature of the water. The inlet water temperatures for the runs made varied to a greater or lesser extent depending on whether an attempt was made to maintain it relatively constant.

SYMBOLS

The following symbols are used in this report:

c_p specific heat of water at constant pressure, Btu/(lb)($^{\circ}$F)

D inside diameter of tube, (ft)

D_o outside diameter of tube, (ft)

G mass velocity of water, (lb)/(hr)(sq ft)

h heat-transfer coefficient, Btu/(hr)(sq ft)($^{\circ}$F)

K thermal conductivity of water, Btu/(hr)(sq ft)($^{\circ}$F/ft)

K_1 thermal conductivity of Inconel, Btu/(hr)(sq ft)($^{\circ}$F/ft)

L heated length of tube, (ft)

q rate of heat transfer to water, Btu/(hr)

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S	heat transfer area of the tube, (sq ft)
T_b	average bulk temperature of water, $(T_1+T_2)/2$ °F
T_o	average outside wall temperature of tube, °F
T_s	average inside wall temperature of tube, °F
T_1	total temperature of water entering tube, °F
T_2	total temperature of water leaving tube, °F
w	water flow rate, (lb/hr)
μ	viscosity of water, (lb)/(ft)(hr)
$\frac{c_p\mu}{K}$	Prandtl number
$\frac{DG}{\mu}$	Reynolds number
$\frac{hD}{K}$	Nusselt number

METHOD OF CALCULATION

The rate of heat transfer was computed from the weight flow, temperature rise, and specific heat at constant pressure for the water flowing through the test-section tube, or,

$$q = wc_p\,(T_2-T_1)$$

The specific heat was evaluated at the average bulk temperature of the water $(T_1+T_2)/2$.

The average outside tube-wall temperature was determined from a plot of wall temperature against tube length. The average inside tube-wall temperature was computed by the equation

$$T_s = T_o - \frac{q}{2LK_1}\,(D_o^2-D^2)\left[D_o^2 \ln \frac{D_o}{D} - \frac{D_o^2-D^2}{2}\right]$$

which, for the tube used in this investigation, simplifies to

$$T_s = T_o - 0.014\ q/K_1$$

This equation may be derived from Fourier's law by considering a tube in which heat generated uniformly by an electric current passing lengthwise in the tube wall is being conducted radially inward. The thermal conductivity of Inconel K_1 was evaluated at the outside tube-wall temperature.

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The heat-transfer coefficient was computed from the rate of heat transfer, the inside surface area of the tube, and the temperature difference between the inside wall temperature and the bulk temperature of the water

$$h = \frac{q}{S(T_s - T_b)}$$

The properties of water used are plotted in figure 5. The thermal conductivity of Inconel is plotted against temperature in figure 6.

RESULTS AND DISCUSSION

Heat-Transfer Data

The heat-transfer data are presented in figure 7. Nusselt number divided by Prandtl number to the four-tenths power $(hD/K)/(c_p\mu/K)^{0.4}$ is plotted against Reynolds number DG/μ. The physical properties of the water are evaluated at the average bulk temperature. Included in figure 7 is the line obtained from the correlation of the data of various investigators (reference 1, p. 168). The equation for this line is

$$\left(\frac{hD}{K}\right)\Big/\left(\frac{c_p\mu}{K}\right)^{0.4} = 0.023\left(\frac{DG}{\mu}\right)^{0.8}$$

The data are satisfactorily correlated by this equation; reasonably accurate results may be obtained in using it to predict heat-transfer coefficients for water under conditions similar to those encountered in this investigation. The scatter about the correlation line in figure 7 can be attributed to the error in the measurement of the rate of heat transfer at high rates of flow where the temperature rise in the water passing through the test section is small.

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Scaling in system. - Prior to the data presented herein, it was noted that the water in the system tended to run acid and to become contaminated with metal oxides after operation at high temperatures. As a possible means of counteracting this tendency, potassium hydroxide was added to the distilled water supplied to the system. The pH of the water in the system during the runs presented herein ranged from 5.3 to 4.1, the tendency being to decrease during a period of operation. The weight of solids in the water of the system was of the order of 50 parts per million. These figures represent an improvement over those obtained previous to the introduction of the potassium hydroxide; however, the extent to which the potassium hydroxide contributed to this improvement is uncertain.

Gas content of water. - Measurements taken of the volume of gas dissolved in the water showed that large amounts were present at the end of each set of runs at 2000 pounds per square inch. The ratio of gas to water volume at room condition was approximately 2. Therefore, it is concluded that the water used in obtaining the data was essentially saturated with nitrogen.

SUMMARY OF RESULTS

Heat-transfer properties were investigated for water flowing at velocities ranging between 5 and 35 feet per second in an electrically heated tube at water pressures of 200 and 2000 pounds per square inch and temperatures in the nonboiling region. It was indicated that the equation Nusselt number = $0.023 \times (\text{Prandtl number})^{0.4} \times (\text{Reynolds number})^{0.8}$ predicts reasonably accurate values of heat-transfer coefficients for water at pressures up to 2000 pounds per square inch and temperatures in the nonboiling region, where the properties of water are evaluated at the average bulk temperature.

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REFERENCES

1. McAdams, William H.: Heat Transmission. McGraw-Hill Book Co., Inc., 2d ed., 1942.

2. Keenan, Joseph H., and Keyes, Frederick G.: Thermodynamic Properties of Steam. John Wiley & Sons, Inc., 1947.

3. Dorsey, N. Ernest: Properties of Ordinary Water-Substances. Reinhold Pub. Corp., 1940, p. 574.

4. Sigwart, K.: Messungen der Zähigkeit von Wasser und Wasserdampf bis ins kritische Gebiet. Forsching, Bd. 7, Heft 3, Mai/Juni 1936, S. 125-140.

5. Timrot, D., and Vargaftic, N.: Heat Conduction of Water at High Temperatures. Jour. Tech. Phys. (USSR), vol. X, no. 13, 1940, pp. 1063-1073.

6. Anon.: Engineering Properties of Inconel. The International Nickel Company, Inc. (New York), March 1950.

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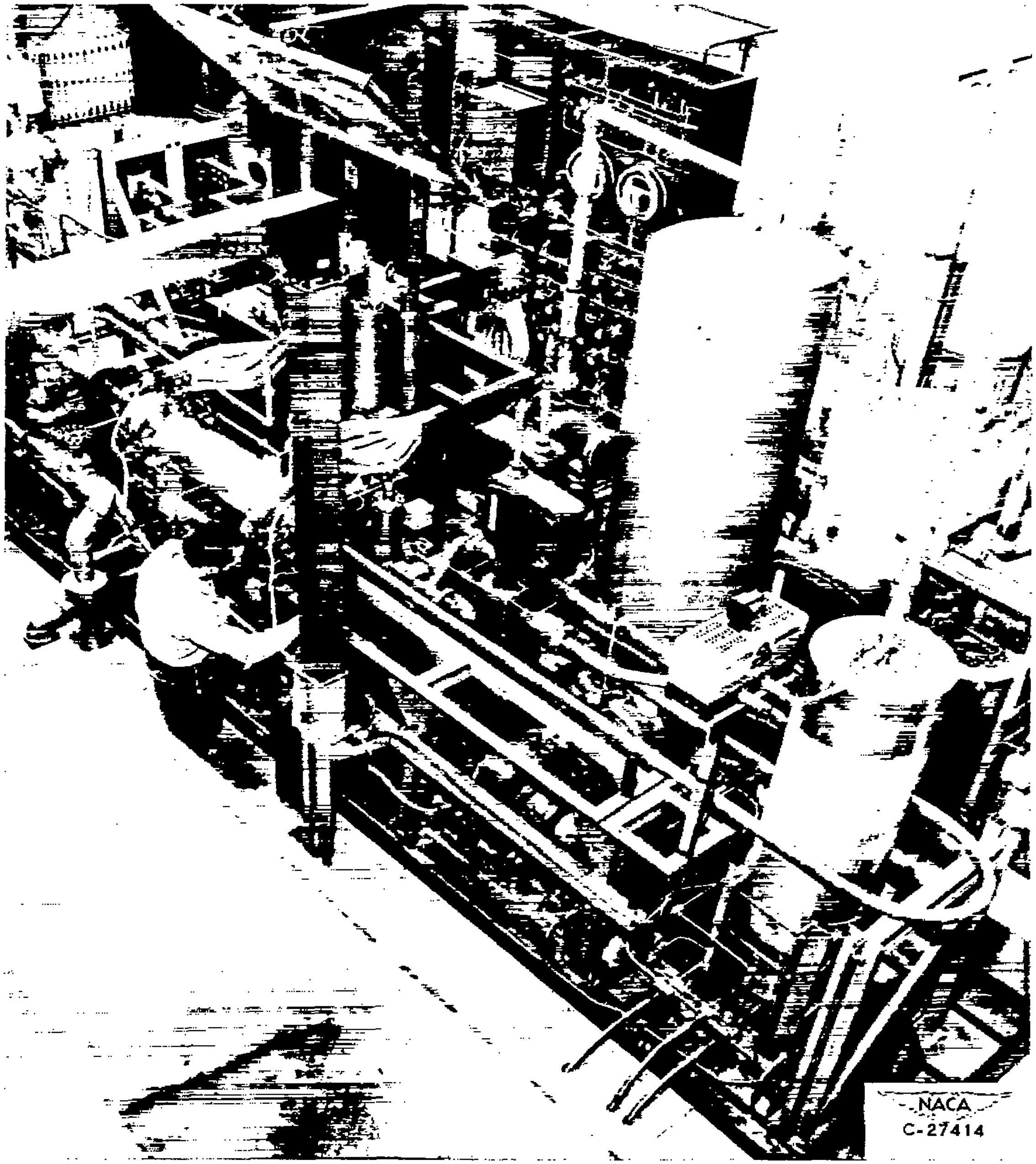

Figure 1. - Photograph of high-pressure-water heat-transfer apparatus.

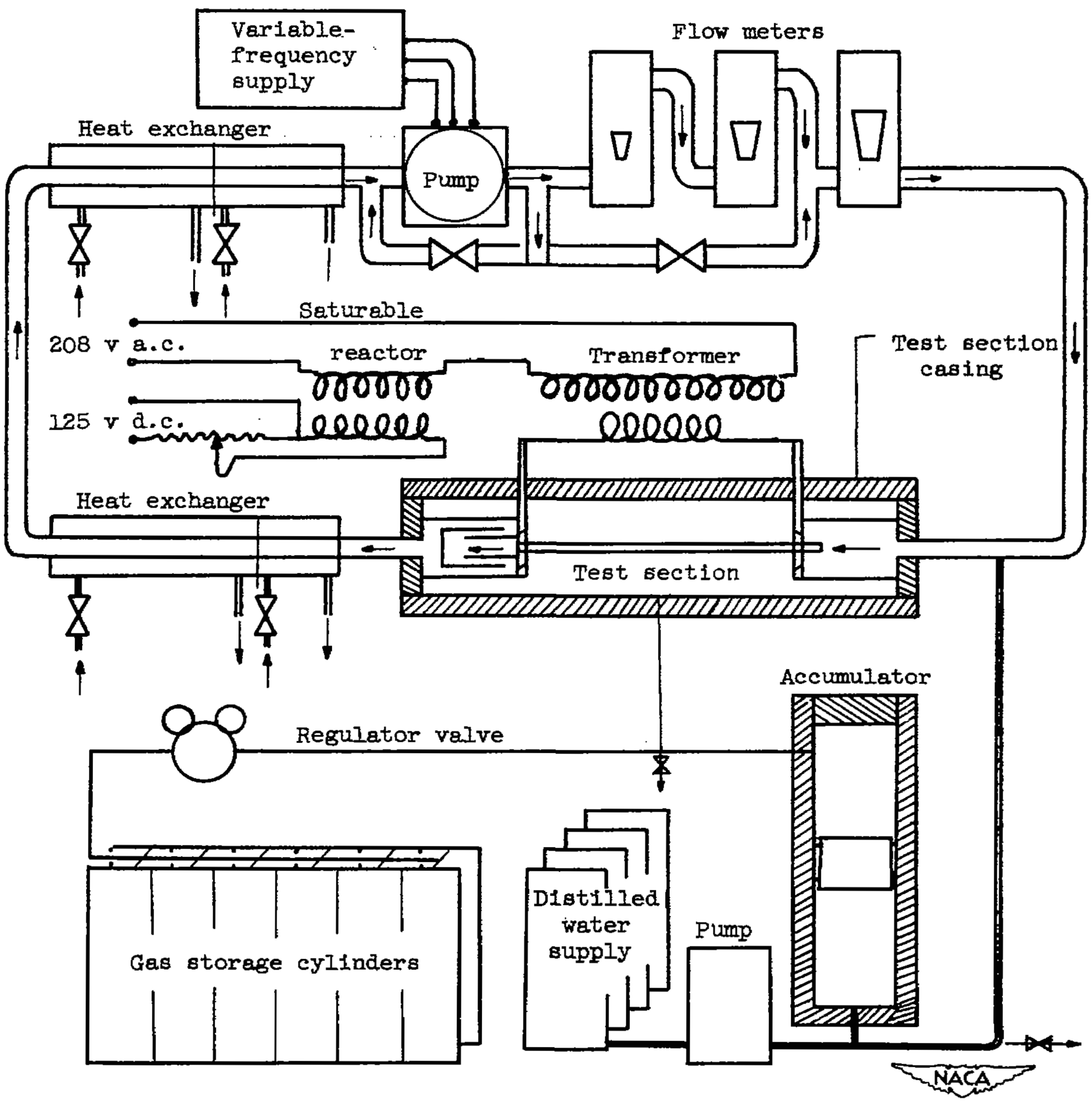

Figure 2. - Schematic diagram showing arrangement of apparatus.

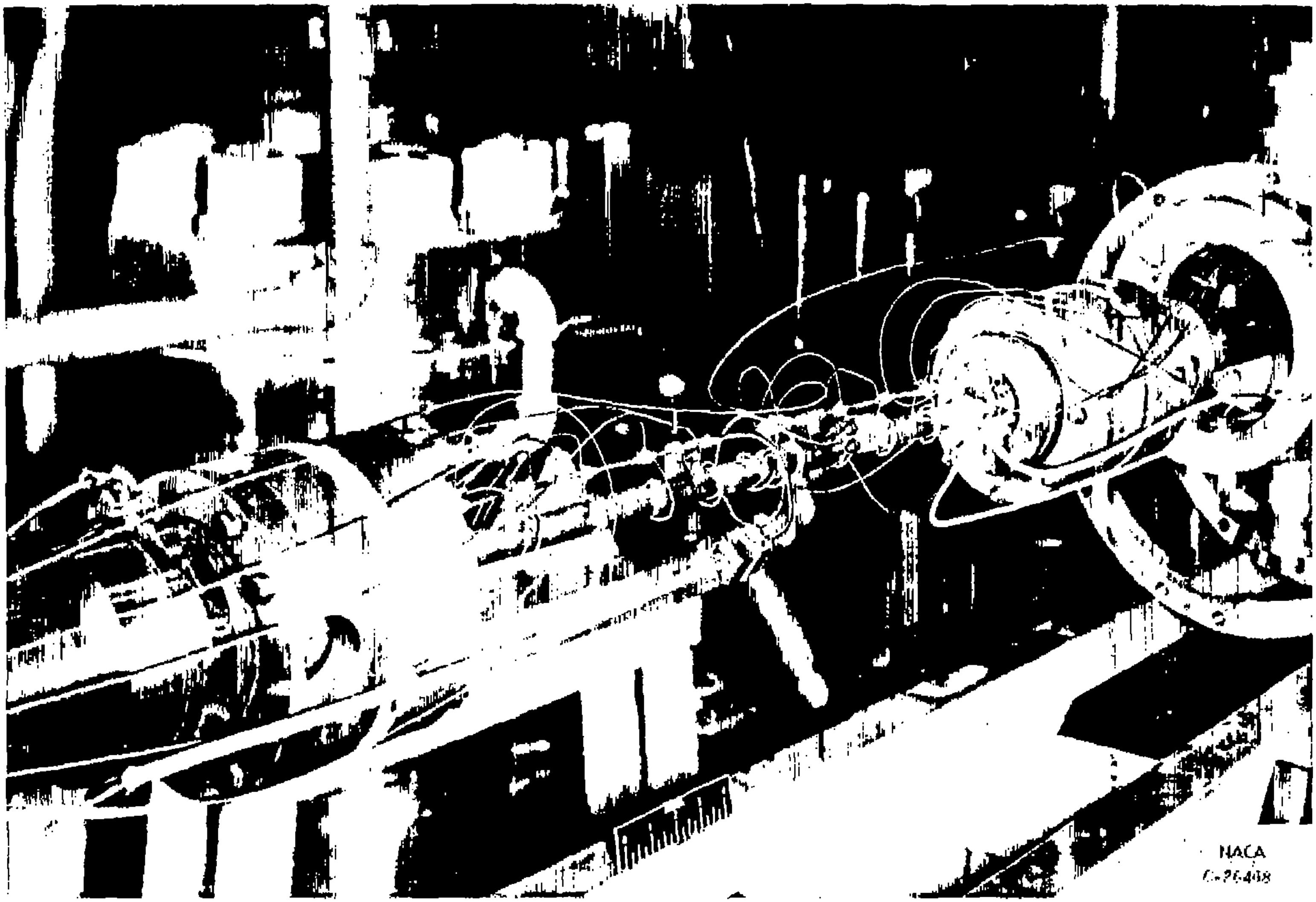

Figure 3. - General view of heater tube installation.

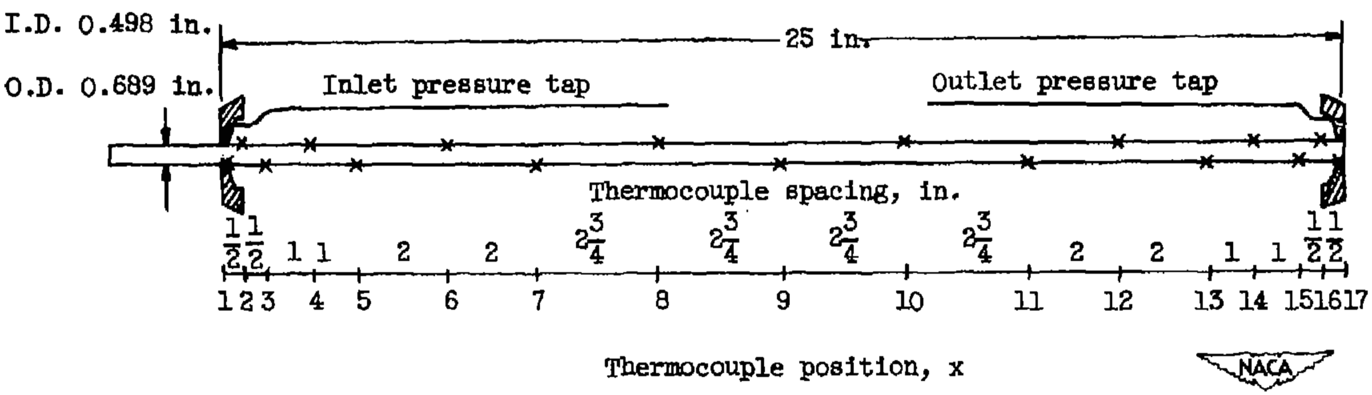

Figure 4. - Schematic diagram of test section tube showing thermocouple and pressure tap locations.

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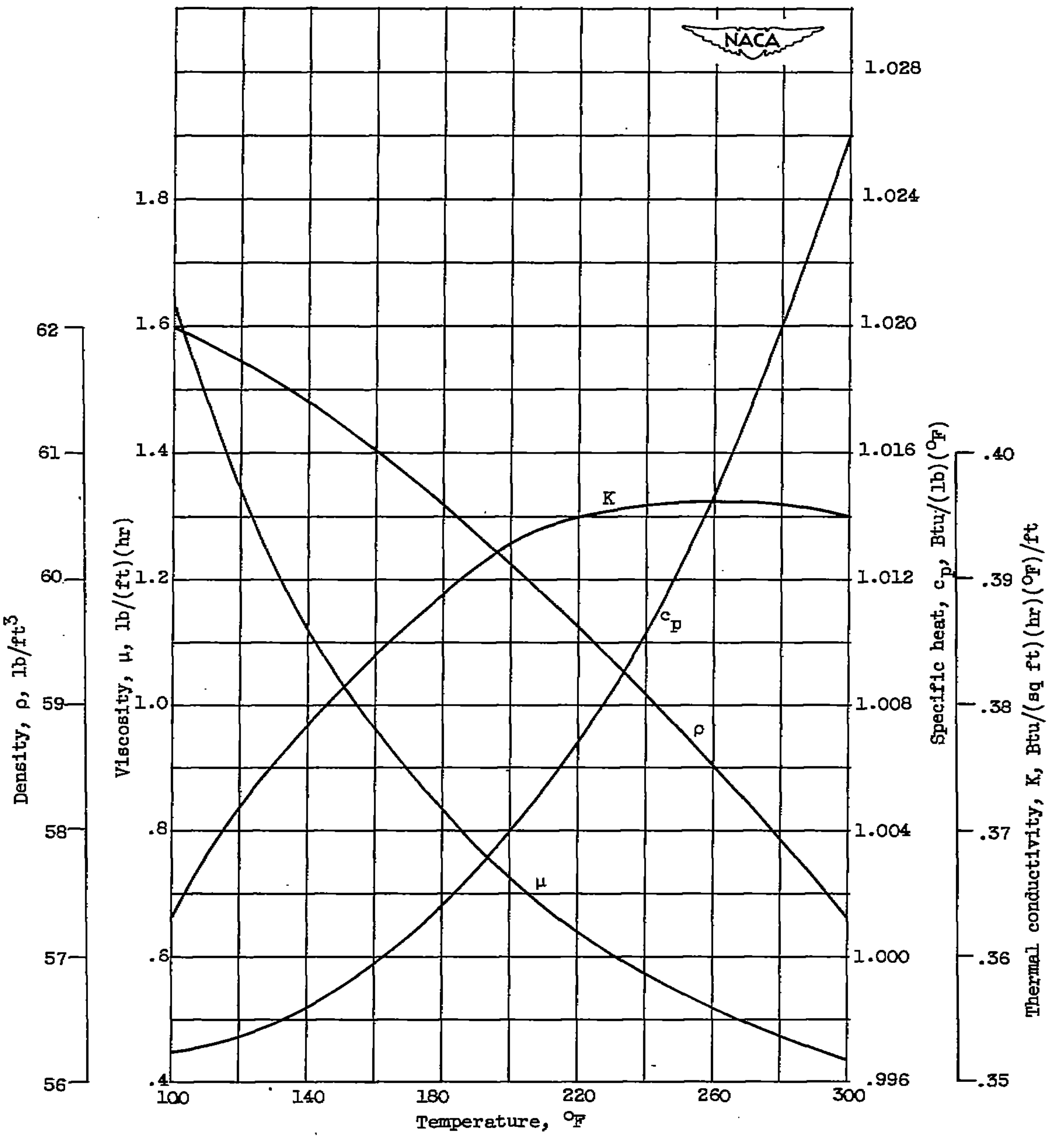
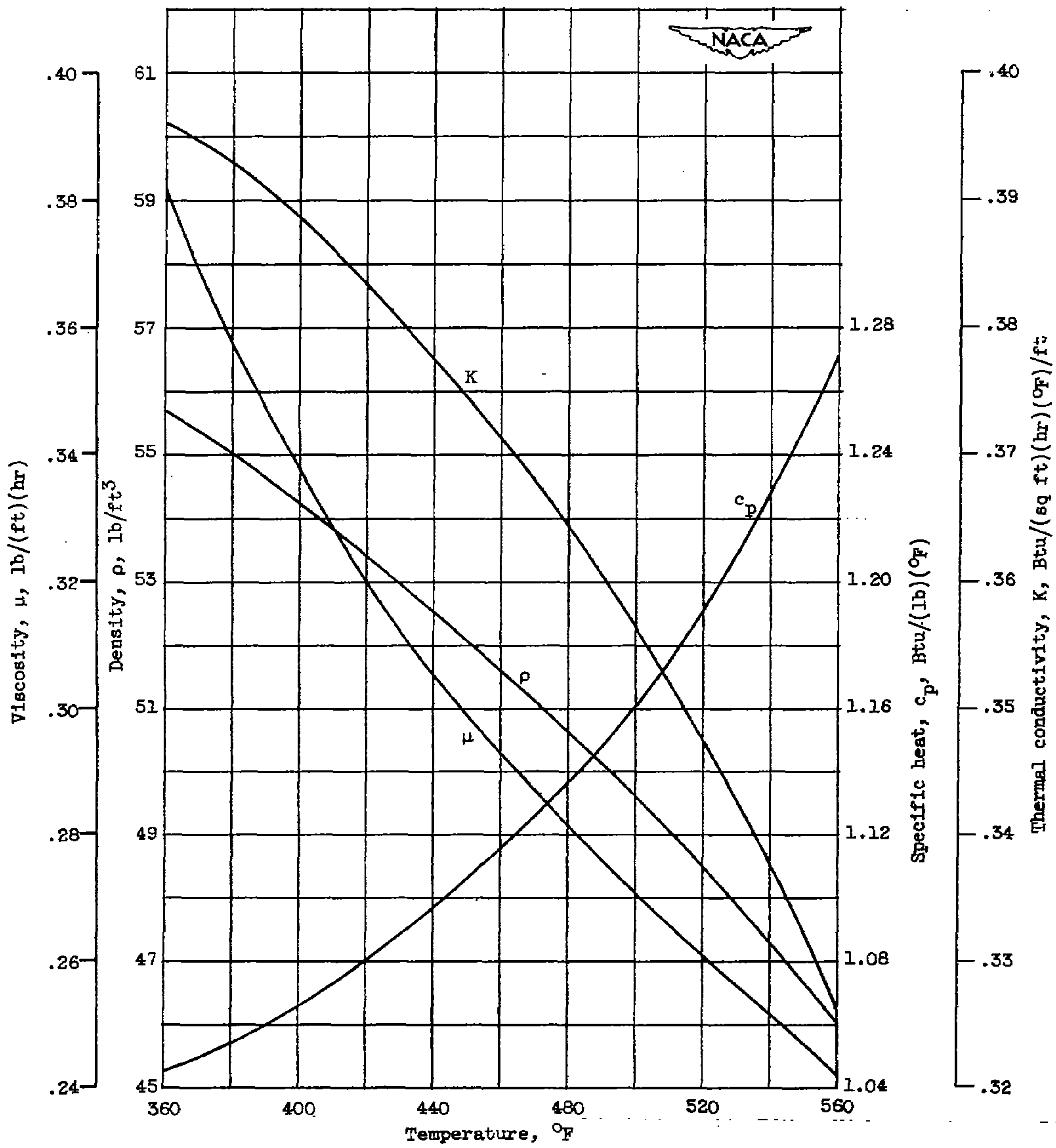


(a) Pressure, 200 pounds per square inch.

Figure 5. - Properties of water. Data for density and specific heat from reference 2; viscosity, references 3 and 4; thermal conductivity, reference 5.



(b) Pressure, 2000 pounds per square inch.

Figure 5. - Concluded. Properties of water. Data for density and specific heat from reference 2; viscosity, references 3 and 4; thermal conductivity, reference 5.

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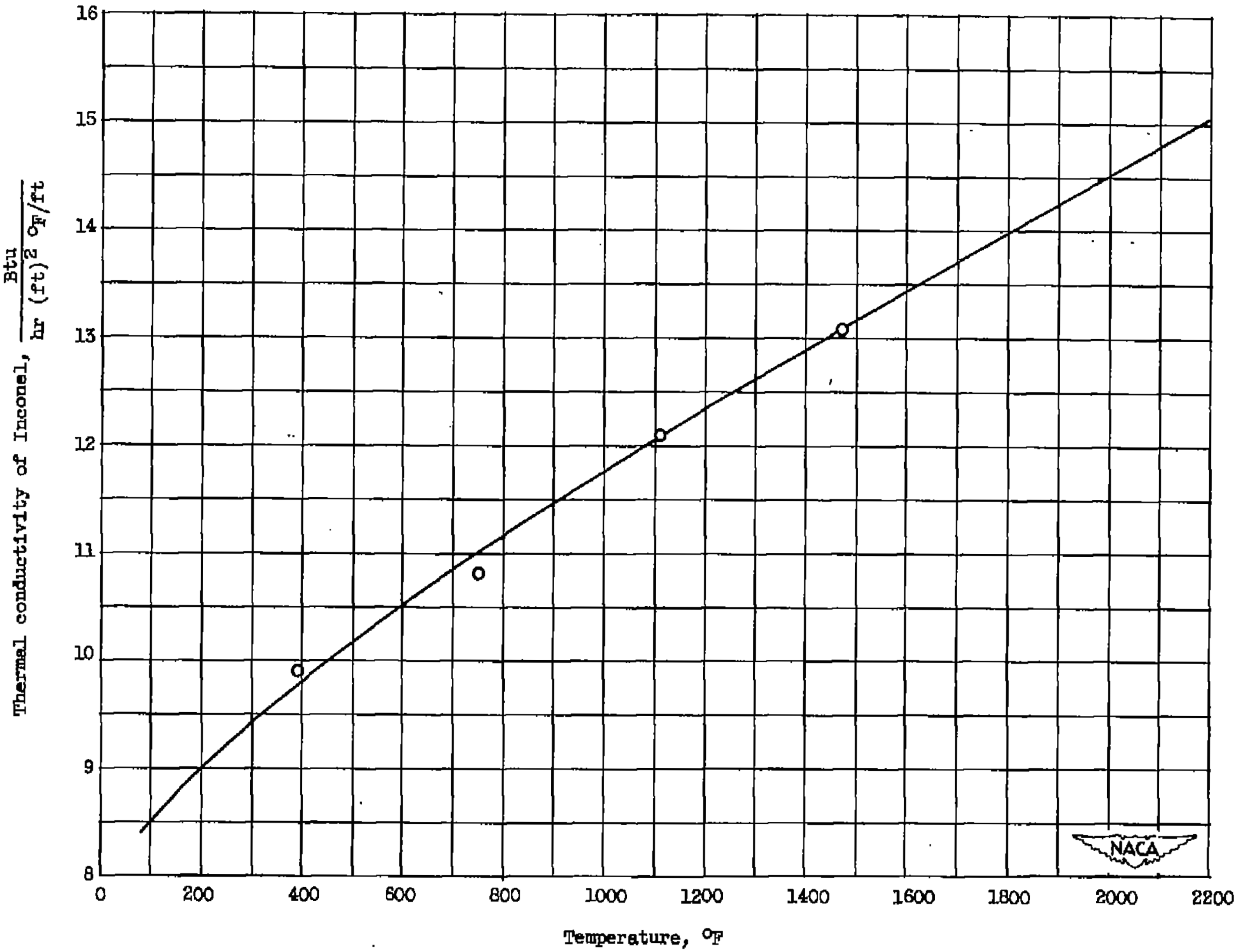

Figure 6. - Thermal conductivity of Inconel based on values given in reference 6.

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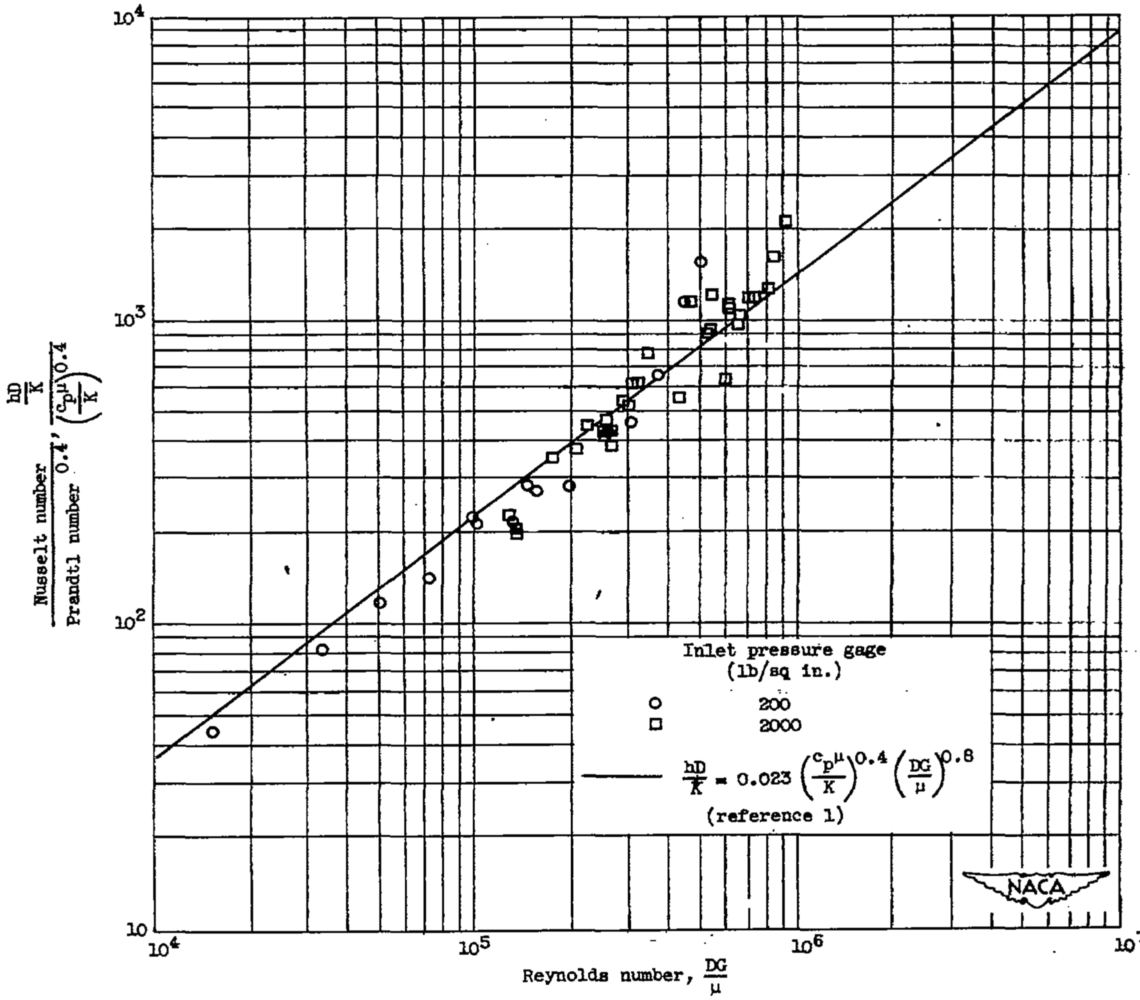

Figure 7. - Correlation of heat-transfer coefficients. Physical properties of water evaluated at average bulk temperature.